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RESULTS OF SOME INITIAL SPACE QUALIFICATION TESTING ON TRIPLE JUNCTION a-Si and $CuInSe_2$ THIN FILM SOLAR CELLS[1]

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ABSTRACT

A series of environmental tests have been completed on one type of triple junction a-Si and two types of $CuInSe_2$ thin film solar cells. The environmental tests include electron irradiation at energies of 0.7, 1.0 and 2.0 MeV, proton irradiation at energies of 0.115, 0.24, 0.3, 0.5, 1.0 and 3.0 MeV, post-irradiation annealing at temperatures between 20°C and 60°C, long term exposure to air mass zero (AM0) photons, measurement of the cells as a function of temperature and illumination intensity, and contact pull strength tests. As expected, the cells are very resistant to electron and proton irradiation. However, when a selected cell type is exposed to low energy protons designed to penetrate to the junction region, there is evidence of more significant damage. A significant amount of recovery was observed after annealing in several of the cells. However, it is not permanent and durable, but merely a temporary restoration, later nullified with additional irradiation. Contact pull strengths measured on the triple junction a-Si cells averaged 667 grams, and pull strengths measured on the Boeing $CuInSe_2$ cells averaged 880 grams. Significant degradation of all cell types was observed after exposure to a 580 hour photon degradation test, regardless of whether the cells had been unirradiated or irradiated (electrons or protons). Although one cell from one manufacturer lost ≈ 60% of its power after the photon test, several other cells from this manufacturer did not degrade at all.

INTRODUCTION

Thin film solar cells have been developed over the past few years primarily for terrestrial applications. Recently developed cells are exhibiting efficiencies that approach the efficiencies of silicon solar cells currently in use on space solar arrays. The most promising thin film solar cells are made of copper indium di-selenide (CIS) and amorphous silicon (a-Si). Preliminary results (refs. 1-4) have also shown that both cell types are very resistant to electron and proton radiation. These attributes of light weight, moderately high efficiencies, and radiation resistance are whetting the interest of many space solar array designers. The purpose of the work reported here was to test and evaluate CIS and a-Si solar cell technology for potential application to space missions.

SOLAR CELLS

The solar cells tested were purchased from three vendors, Boeing and ISET for the $CuInSe_2$ cells and Solarex for the triple junction a-Si cells. The Boeing cells were made by a physical vapor deposition of the CIS film from multiple elemental sources in a vacuum (refs. 5,6). The ISET cells were made by the selenization of electron-beam-evaporated Cu-In films in a H_2Se atmosphere, followed by deposition of thin

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CdS and ZnO window layers (ref. 7). The Solarex cells were made by the DC plasma assisted CVD technique (ref. 8). The cell structures of all three cell types are diagrammed in Figure 1. The CIS cells were all made on 500 μm-thick glass substrates and were constructed so that both the n and the p contacts were accessible from the front cell surface. The Solarex cell was made with a 500 μm-thick glass superstrate. It was made of OCLI 0213 Ce-doped coverglass material so that radiation darkening of the glass would not obscure the results of the cell's radiation testing. The Solarex cell contacts were both accessible from the rear cell surface.

Since most of the cells used in these tests were manufactured primarily for terrestrial use, an initial purchase was made of a few cells from each vendor in order to see if there would be any problems with the way the cells would interact with our test probes and procedures. Contact structure modifications were found necessary on the ISET and Solarex cells, and the manufacturers were very cooperative in modifying the contacts for us. A second batch of modified cells was purchased with the contacts compatible with space testing procedures. The cells procured for these tests were quite expensive because they are not available in production quantities. However, we were able to purchase a sufficient quantity of cells so that a sample size of at least three was used in nearly all the experiments.

SOLAR CELL ELECTRICAL TESTS

All solar cells were electrically characterized before and after any of the tests reported here by measuring their I-V characteristics and their spectral responses. The I-V measurements were performed using a Spectrolab X-25 Mark II solar simulator as the light source. Its illumination level was set to air mass zero (AM0) intensity (136.7 mW/cm^2) using an appropriate balloon flight standard. Special fixtures were constructed for measuring each cell type. The fixtures used spring loaded probes to contact the cells. During the measurements, the cells were held at 28°C. The computer program and electronics ordinarily used for measuring the I-V characteristics of crystalline Si and GaAs cells was used for these measurements without modification.

I-V measurements were obtained on thirty Boeing CIS cells, twenty-nine ISET CIS cells, thirty-one Lot I Solarex triple junction a-Si cells and twenty Lot II Solarex triple junction a-Si cells (The Solarex cells were divided into two lots because they had noticeably different I-V and spectral response characteristics). The averaged values for the initial AM0 electrical parameters are summarized in Table I. Conversion efficiencies were computed by using the active areas listed in the table. Active areas were used in the calculations for comparison purposes because some cells had very large contact pads outside the cell area and would be much smaller in production cells.

The JPL spectral response apparatus was modified for measurements of the triple-junction a-Si cells. As reported in ref. 9, this involved the measurement of each cell three times. During each measurement the dc bias light was filtered in such a manner that first junctions 2 and 3 were turned on by the filtered light so that only junction 1 responded to the chopped light from the monochromator. Then the filter was replaced by a second filter which turned on junctions 1 and 3, while junction 2 was measured, and so on. The overall spectral response of the cell is then computed by summing the three curves measured in this manner.

CONTACT STRENGTH TEST RESULTS

Cell contact pull strength tests were completed on the Boeing CIS and the Solarex Triple Junction a-Si cells. No attempt was made to solder or weld to the aluminum contacts on the ISET CIS cells. L-shaped leads consisting of pure silver ribbon (0.1mm X 0.5mm) were soldered to the cell contacts using Sn62 (2% Silver) eutectic solder. Care was taken to minimize soldering iron temperature and soldering time (≈ 2 seconds). The 5mm length of the "L" was soldered to the cell contact. The 15mm length of the "L" was used to pull the contact at a 90 degree angle from the cell surface. The pull rate was ≈ 3cm/minute and

the temperature of the pull samples was 20 ±2 degrees C. The results, shown in Table II, reveal that the contact pull strengths of the cells test was satisfactory.

PROTON IRRADIATION TEST RESULTS

The proton irradiations were performed on the CalTech tandem Van de Graaff accelerator. The beams were spread laterally by passing the proton beams through appropriate chromium or gold scattering foils to produce a beam uniformity of better than ±5% over a 10-cm diameter circle at the target plane. A small Faraday cup at the center of the target plane was used for measuring flux and fluence. The target plane remained at room temperature with no need for active thermal control at the low flux rates used. The cells were attached to the target plane with double-backed adhesive tape. Immediately after irradiation, the cells were removed from the target area and packed in dry ice until electrical measurements began.

Four sets of thin film cells were selected for proton testing. Each set consisted of three of the Boeing, ISET and Solarex Lot I and two of the Solarex Lot II cells. Each set was exposed to a specific proton energy to a schedule of fluences ranging between 1 x 10^9 and 2 x 10^{12} p/cm^2. The proton energies were 0.5, 1.0, and 3.0 MeV for all cell types plus a specific low energy for each cell type. In the case of the CIS cells, these energies were 300 keV for the Boeing cells and 240 keV for the ISET cells. These energies were chosen so that they would stop after penetrating most of the way through the topmost semiconductor layer, at which point they are expected to produce the maximum amount of damage in the cell. The specific energy chosen for the Solarex cells was 115 keV. This proton energy was calculated to stop in the center of the topmost junction of these cells when the protons were incident from the rear. The analysis of the energy absorption of the cell materials was based upon material and thickness information obtained from the cell manufacturers, and the errors made in the calculation will vary as the thickness tolerances and material densities vary. It was found that 500 keV protons would just penetrate all the semiconductor layers of both CIS cell types, and would penetrate all the layers and stop in the superstrate glass in the Solarex cell.

The normalized P_{max} curves of Figures 2 through 5 summarize the results of the proton irradiations prior to annealing. It is clear that the lowest energy protons which stopped in the top layer of the CIS cells produced very little, if any, damage to the cells. But as the energy was increased to the value that just completely penetrated the CIS cells, 500 keV, the damage was substantial. As the energy was increased to 1 MeV, the damage decreased, and as the energy was increased to 3 MeV, the damage decreased even further. The Solarex cells appear to degrade significantly after bombardment with only one energy, 115 keV. These protons stop in a vulnerable part of the cell while the higher energies pass on through mostly without stopping anywhere in the active part of the cell. While the data for all three cells is too sparse for a precise determination, it may be that the cells are all degrading in accordance with the energy dependence for proton-induced displacement damage of lnE/E (ref. 10). This line of reasoning also tells us that proton energies between 300 and 500 keV may cause a great deal of damage in the ISET and Boeing cells, and energies between 46 keV (the energy required to penetrate to the third junction) to 500 keV may also cause a lot of damage in these a-Si cells.

After the cells had been irradiated to a fluence of 1 x 10^{12} p/cm^2, and characterized electrically, they were annealed at ≈ 20°C for 14 days, then remeasured. They were they placed in a 60°C air oven for 18 hours, and again measured. At this point the cells were irradiated with an additional 1 x 10^{12} p/cm^2, and the annealing process repeated (here a 35 day anneal at 20°C was used).

The results of the annealing experiments are summarized in the normalized P_{max} curves shown in Figures 6 through 9, which show the power remaining after the final 60°C anneals. The total amount of annealing can be computed by a comparison with the matching unannealed curves of Figures 2 through 5. We can make some observations about the annealing behavior. It is possible to anneal out a great deal of the damage produced by low energy protons in all the cells, but the damage produced by the higher energies of 1 and 3 MeV anneals very little. The annealing at 20°C is responsible for the major share of the

recovery. In general, the additional improvement due to the 60°C anneal was only about half the recovery achieved by the 20°C treatment.

ELECTRON IRRADIATION TEST RESULTS

The electron irradiations were performed on the JPL Dynamitron accelerator with the samples held at 28°C during the irradiations. The electron beams were spread laterally with appropriate aluminum or copper scattering foils to give a beam uniformity of better than ±5% over the target plane. The cells were held in thermal contact with the temperature controlled target plane by a thin layer of Apiezon H vacuum grease. In most cases, the cells were measured electrically within a few minutes after irradiation, but in those cases where it would be several hours before measurements could be initiated, the cells were placed in a freezer to minimize annealing.

Three sets of cells consisting of three of the Boeing, ISET and Solarex Lot I and two of the Solarex Lot II cells were exposed to 0.7, 1.0, and 2.0 MeV electrons. Each set of cells was individually exposed to cumulative fluences between $3X10^{13}$ and $1X10^{16}$ e/cm^2 in ≈half order of magnitude steps. The Boeing and ISET cells were exposed to the electrons through their front surfaces, but the Solarex cells were exposed through their rear surfaces so the electrons would not have to first penetrate the superstrate glass. Since the thickness of the actual cell structure is less than 1/100 of the range of 700 keV electrons, the incidence direction matters very little as long as we avoid irradiating through the relatively thick glass supports. I-V measurements were taken after each radiation exposure. Observed changes in normalized maximum power (P_{max}/P_{max0}), before annealing, are shown in Figures 10, 11, 12 and 13. A plot of the normalized power behavior of a crystalline silicon cell (ASEC 10 Ω-cm, BSR, dual AR) irradiated with 1 MeV electrons is included in the figures for comparison.

All cells were annealed at low temperatures after they reached fluences of $1X10^{15}$ e/cm^2. The first anneal was at room temperature (20°C), and the second anneal was at 60°C in an air oven for ≈ 18 hours. I-V measurements were made after each annealing step. The cells were then irradiated to a cumulative fluence of $3X10^{15}$ e/cm^2 and the annealing steps were repeated. The cells were then irradiated to a cumulative fluence of $1x10^{16}$ e/cm^2, measured, annealed at room temperature for three to five days, and finally annealed at 60°C again for 20 hours. The results of the annealing experiments following the $1X10^{15}$, $3X10^{15}$ and $1x10^{16}$ e/cm^2 fluences are shown in the normalized P_{max} plots of Figures 14, 15, 16 and 17, along with a comparison curve for the ASEC Si cell.

Under electron irradiation, conventional Si and GaAs cells degrade more as the energy is increased. This is in agreement with displacement damage theory as predicted by displacement damage theory. This was also true for CIS cells irradiated to fluences less than ≈ 1×10^{15} e/cm^2, but at higher fluences the 700 keV and 2 MeV electrons were both more damaging than 1 MeV electrons. In contrast, the a-Si cells degraded less with increasing electron energy, indicating that displacement damage is not the only mechanism which is degrading these cells.

It is also clear from the plots of both annealed and unannealed P_{max} data that the crystalline Si cells begin degrading at low fluences, while the thin film cells exhibit very little degradation until they have been exposed to ≈ 1×10^{15} e/cm^2, at which point their degradation rate increases markedly. The losses in all the cells appear to be about equally shared between losses in V_{oc} and I_{sc}.

All the thin film cells tested here exhibit a much greater recovery of their damage when annealed at low temperatures than the crystalline Si cells. In most cases it was observed that the more the cell was damaged by radiation, the more it will anneal. Examples are the Solarex and ISET cells, heavily degraded after receiving fluences of 1×10^{16} e/cm^2, which all recovered from 10 to 25% of their pre-irradiation power after the 20° and 60°C anneals. The Boeing cells, less severely damaged, all recovered to within at least 97% of their pre-irradiation values. All cells showed significant recovery after the 2 to 5 day 20°C anneal. The CIS cells all annealed at least as much at room temperature as they did at 60°C, and in some cells the 60°C anneal did not induce any additional recovery at all. The behavior of the cells after irradiation and

annealing, followed by additional irradiation is worthy of comment. It was observed in all cases, that the annealed cells upon receiving their next electron dose, appeared to immediately revert to the state they had been in prior to the annealing, then proceeded to follow an unannealed degradation curve from there on. However, at the moment this observation is rather speculative and would have to be confirmed by performing additional experimentation.

PHOTON DEGRADATION TEST RESULTS

Samples of the three types of cells also underwent long term exposure to air mass zero (AM0) photons for a period of 580 hours. A Spectrolab X-25L was used as the light source. The cells were tested in atmosphere under open circuit condition, and were temperature controlled to 20°C. Proton irradiated, electron irradiated and non-irradiated samples from all three manufacturers were tested. The cells were removed from the exposure fixture for electrical characterization after exposures of 21, 90, 158, 275, 443, and 580 hours.

The proton irradiated cell group consisted of eight cells (two Boeing, two ISET, two Solarex Lot I and two Solarex Lot II) which had been heavily damaged by protons then subjected to the annealing schedules discussed previously. The electron irradiated cell group also consisted of eight typical, 60°C annealed cells that had all been irradiated to 1 X 10^{16} e/cm^2. This included one cell each of the four types that had been irradiated with 0.7 MeV electrons, and one cell of each type that had been irradiated with 1 MeV electrons. Eight non-irradiated cells were also included in the test, two from each cell type.

There are some inconsistencies in the results of this test in that it gave poor agreement with a similar test run earlier at JPL. However, some observations may be made. All cell types were observed to degrade with photons, but it takes about 40 hours of exposure to produce a noticeable degradation in most cells. In general, the cells which had been irradiated heavily with either electrons or protons did not degrade as much as unirradiated cells. The degradation of the Solarex cells matched previously observed results at both Solarex and JPL wherein the maximum power dropped ≈ 20% after 500 hours of photon exposure. The CIS cells degraded significantly differently than in previous experiments. Some cells did not degrade at all, and some types that had not degraded at all or only slightly in earlier experiments were seen to degrade a great deal. The reason for these discrepant results is still under investigation.

CONCLUSIONS

Although the thin film cells measured here are very promising, they are probably not yet ready for space use. On the plus side, their radiation resistance to both protons and electrons is generally superior to crystalline Si and GaAs solar cells and the heavy radiation damage induced in thin film cells by both electrons and protons can be mitigated by annealing at fairly low temperatures. All the thin film cells examined here are easily damaged by low energy protons which stop in the active areas of the cells, but the cells can easily be shielded from these protons. The efficiencies are low in comparison with crystalline Si and GaAs cells (the highest efficiency cell measured here was 9.5%), but the potential for making very light weight cells is very good. Photon degradation remains a problem, not only for the a-Si cells, but for the CIS cells as well. Contacts continue to be a problem with some of the thin film cells. Although the contact pull strengths on the cells tested were found to be satisfactory, making contact with the cells was quite difficult and in some cases impossible. The cells we procured for this task were purchased from research laboratories, and the cells experienced an amount of variability in their characteristics that might be expected from cells made in that environment. We are left with the nagging feeling that some of the conclusions drawn here are the result of manufacturing variability. We believe the next step in examining the readiness of these cells for space, will have to involve homing in on a promising manufacturing process, setting up a pilot line, then producing a large quantity of test cells using that process.

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Table I. Initial Electrical Parameters for Tested Thin Film Cells

Manufacturer	I_{sc} (mA)	V_{oc} (mV)	P_{max} (mW)	Active Area (cm^2)	Eff. (%)
Boeing	171.6	408.9	45.25	4.0	8.28
ISET	144.6	452.3	38.73	3.62	7.83
Solarex Lot 1	50.0	2242.9	67.91	7.0	7.10
Solarex Lot 2	45.7	2244.8	51.80	7.0	5.41

Table II. Results of 90 Degree Angle Cell Contact Pull Strength Tests

Cell Mfg	Pull Strength	Std. Dev.	Failure Mode
Boeing	880 grams	± 65 grams	50% Solder 50% Pull Wire
Solarex	667 grams	± 144 grams	Cell Metallization

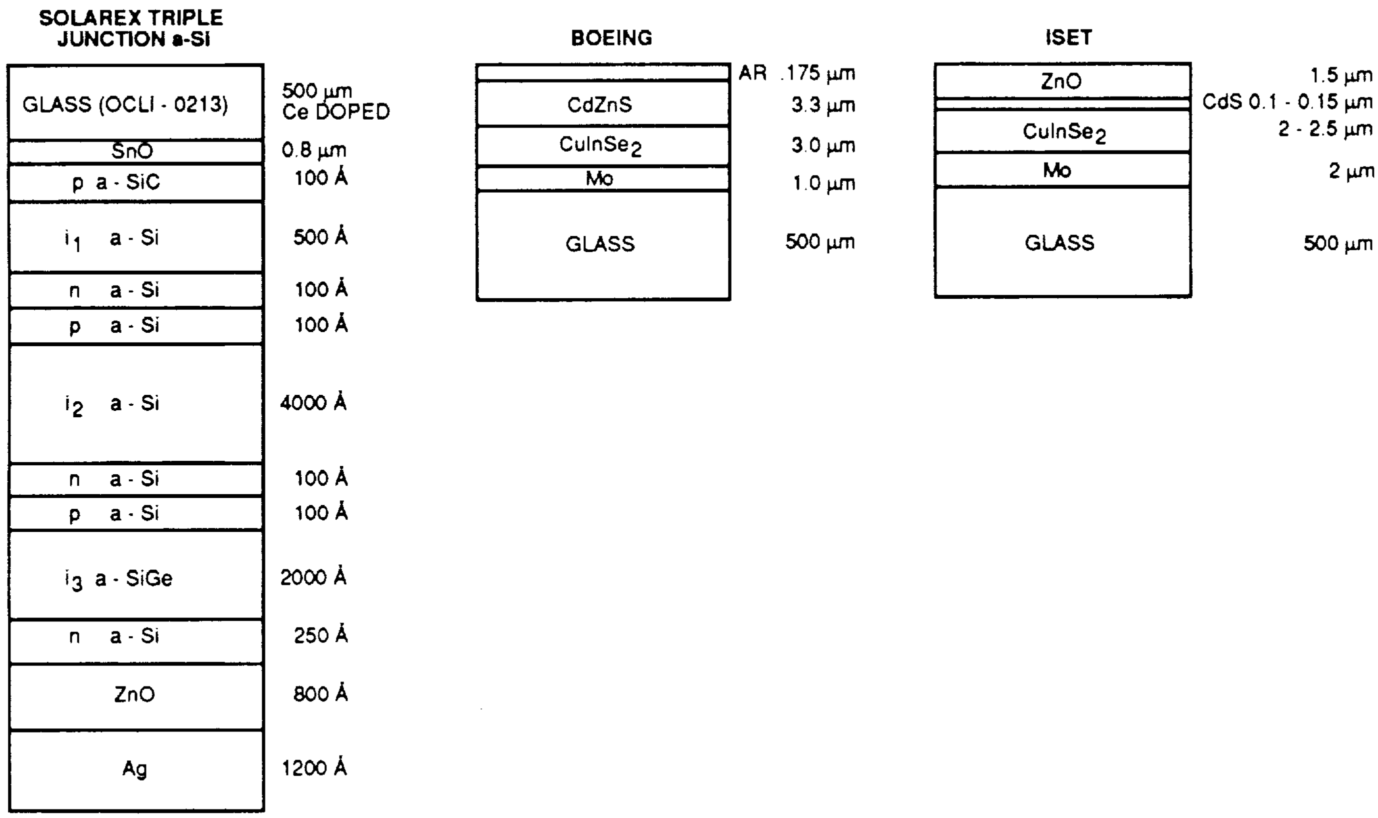

Figure 1 Cross-sections of the Thin Film Solar Cells

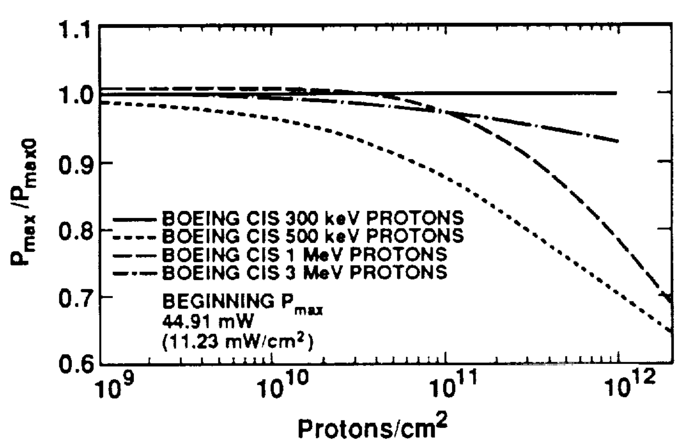

Figure 2 Proton Irradiation Results for Non-annealed Boeing CIS Cells

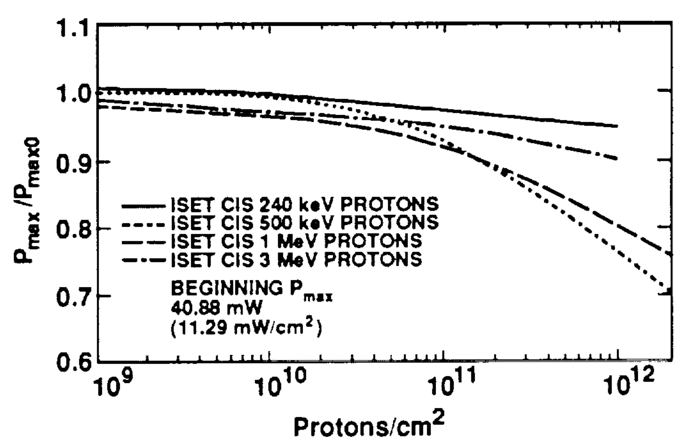

Figure 3 Proton Irradiation Results for Non-annealed ISET CIS Cells

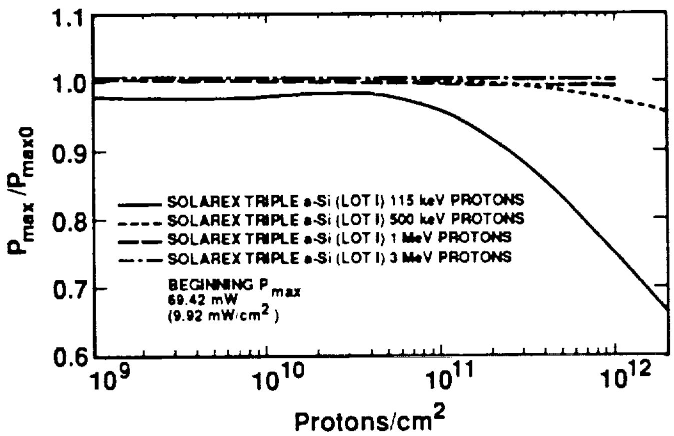

Figure 4 Proton Irradiation Results for Non-annealed Solarex Lot I Triple Junction a-Si Cells

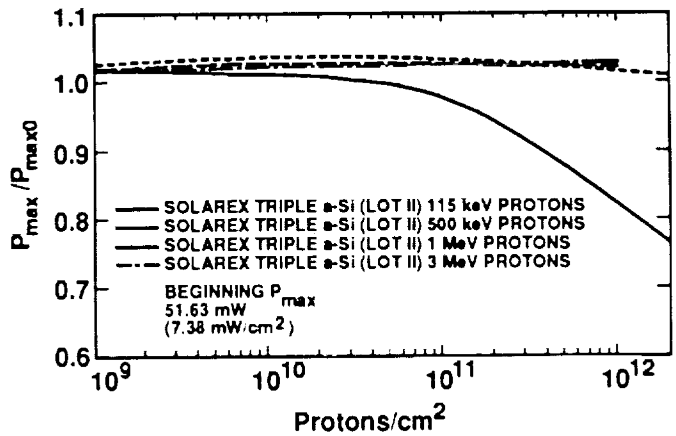

Figure 5 Proton Irradiation Results for Non-annealed Solarex Lot II Triple Junction a-Si Cells

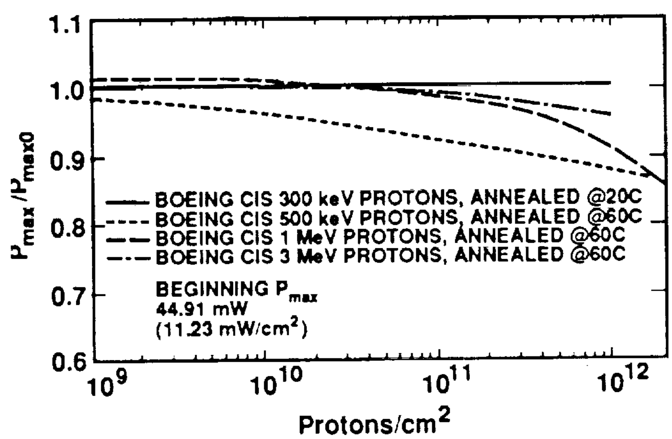

Figure 6 Proton Irradiation Results for 60°C Annealed Boeing CIS Cells

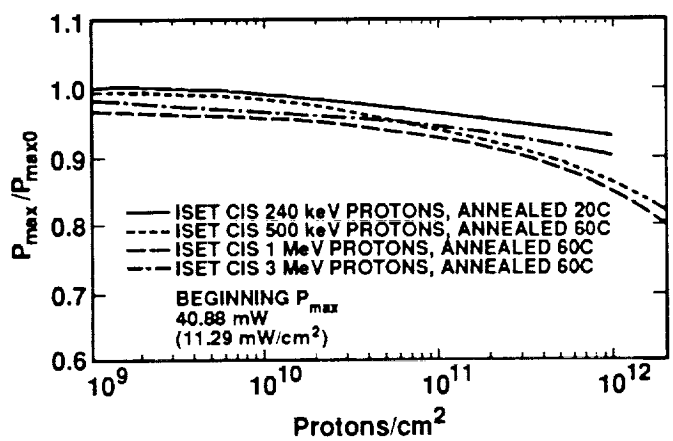

Figure 7 Proton Irradiation Results for 60°C Annealed ISET CIS Cells

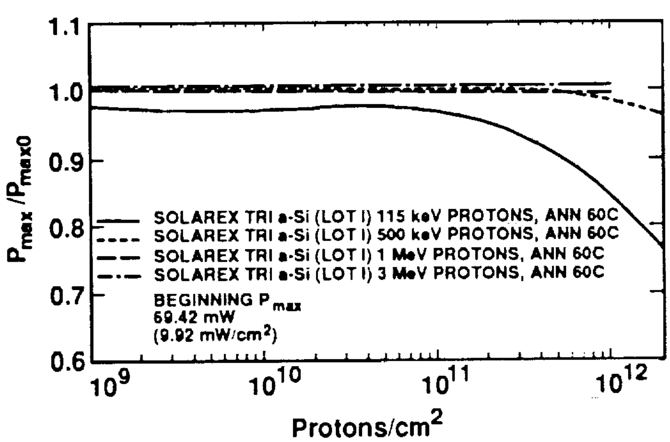

Figure 8 Proton Irradiation Results for 60°C Annealed Solarex Lot I Triple Junction a-Si Cells

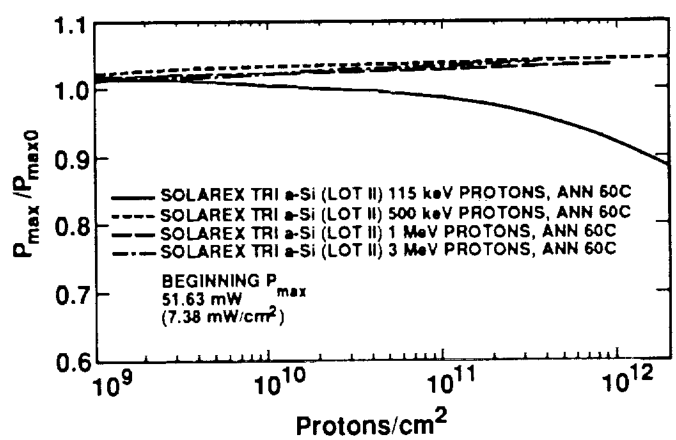

Figure 9 Proton Irradiation Results for 60°C Annealed Solarex Lot II Triple Junction a-Si Cells

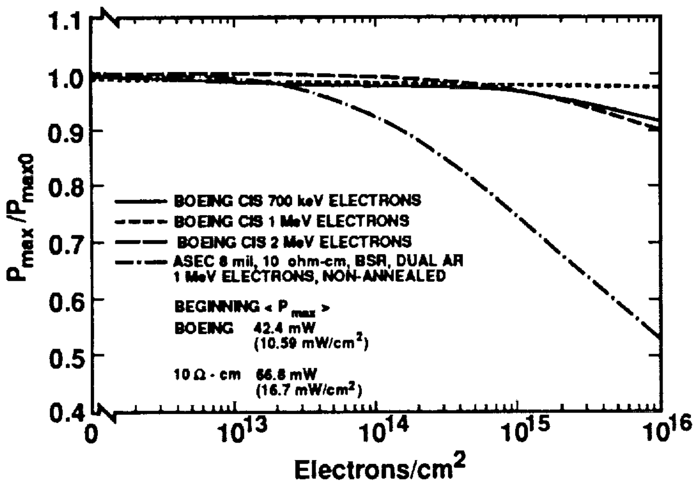

Figure 10 Electron Irradiation Results for Non-annealed Boeing CIS Cells

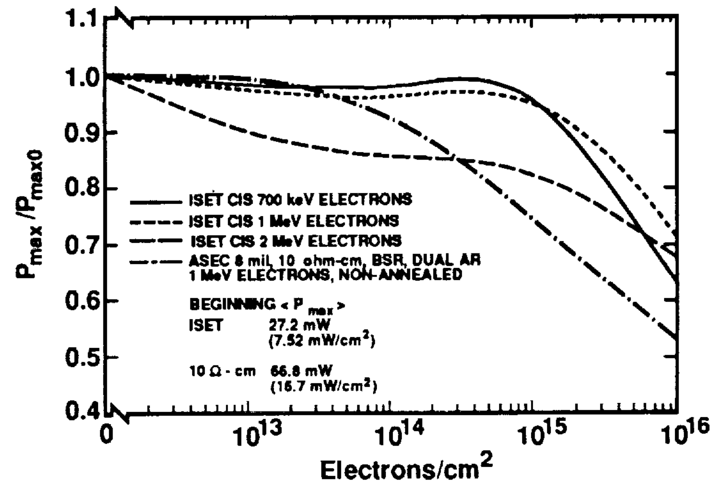

Figure 11 Electron Irradiation Results for Non-annealed ISET CIS Cells

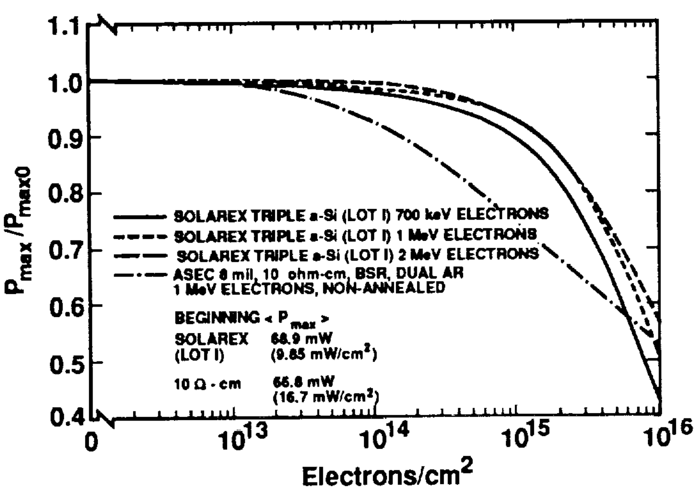

Figure 12 Electron Irradiation Results for Non-annealed Solarex Lot I Triple Junction a-Si Cells

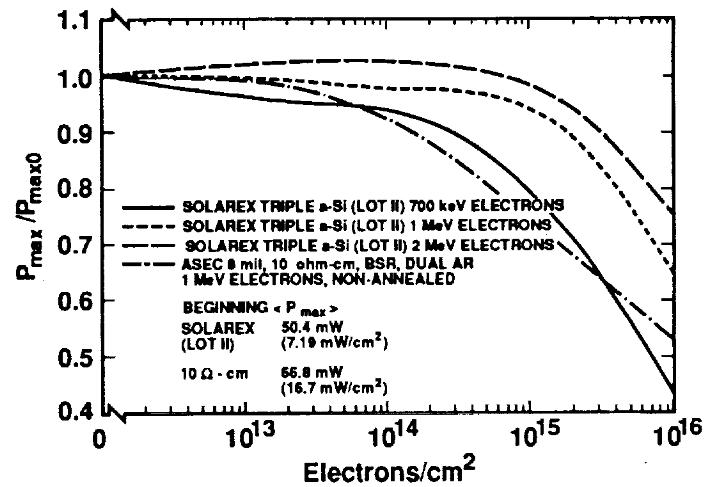

Figure 13 Electron Irradiation Results for Non-annealed Solarex Lot II Triple Junction a-Si Cells

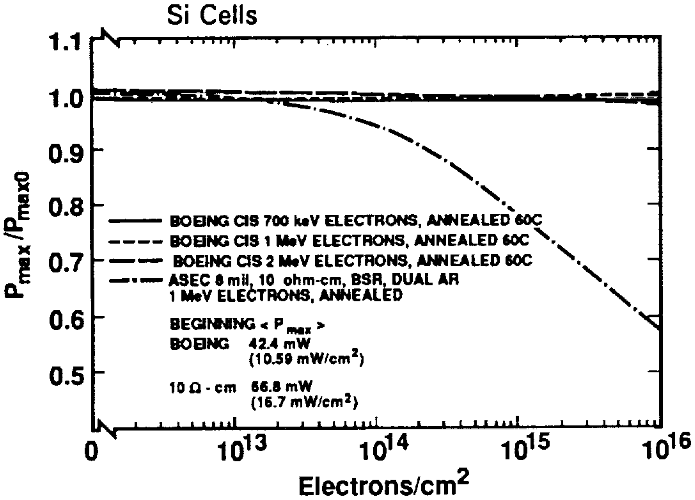

Figure 14 Electron Irradiation Results for 60°C Annealed Boeing CIS Cells

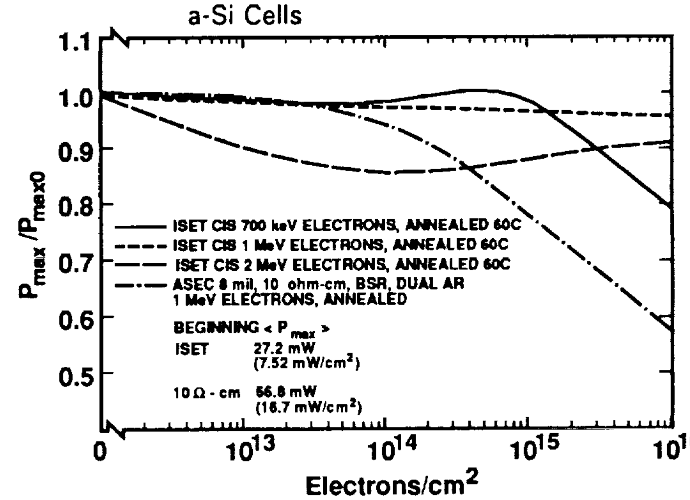

Figure 15 Electron Irradiation Results for 60°C Annealed ISET CIS Cells

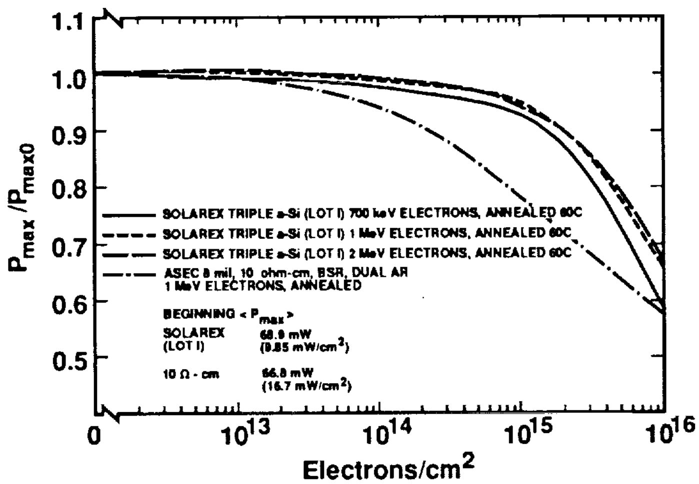

Figure 16 Electron Irradiation Results for 60°C Annealed Solarex Lot I Triple Junction a-Si Cells

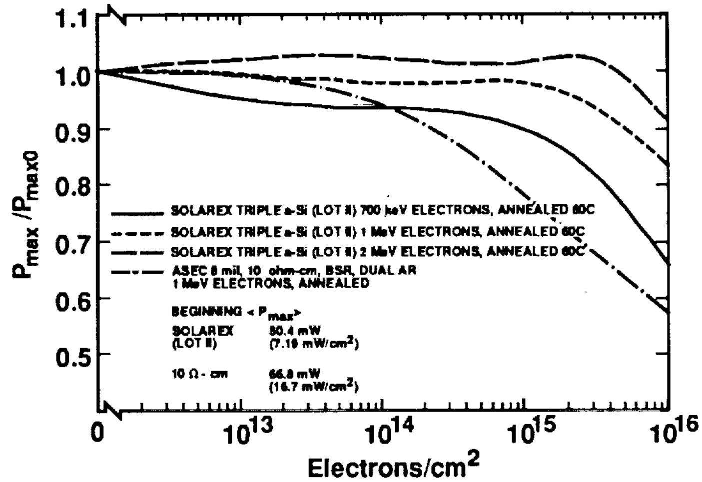

Figure 17 Electron Irradiation Results for 60°C Annealed Solarex Lot II Triple Junction a-Si Cells